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PROGRESS REPORT

SURVEY OF GAS TURBINE CONTROL
FOR APPLICATION TO MARINE GAS
TURBINE PROPULSION SYSTEM CONTROL

by

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The Marine Gas Turbine control systems in present use in the US Navy are of significant technological age that new design techniques and micro-processing abilities could lead to more optimal performance and increased plant efficiency. This paper reviews current design theory approaches for aviation gas turbine control and advances in digital control. This review shows that todays technology presents the opportunity to redesign control systems for marine gas turbine propulsion and thereby increase its operating performance.

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INTRODUCTION: Modern day controllers for marine propulsion gas turbines systems in today's Navy are of the mechanical type developed over twenty years ago (1). With the U.S. Navy's commitment to gas turbine propulsion well into the next century (2) a more modern, efficient, reliable and flexibly compatible control system must be designed to meet the needs of the future (3). Mechanical controllers with their size and number of components can be maintenance nightmares which require vast stock resources and extensive training programs for maintenance personnel. In contrast, advances in microprocessor technology and control design theory make possible the creation of a new generation of control systems which offer digital compatibility, redesign flexibility and simplicity; these attributes could reduce the maintenance problems as well as increase existing naval marine propulsion plant efficiencies.

The U.S. Navy's approach to large vessel marine propulsion has been to purchase an aero derivative gas turbine, the General Electric LM-2500. G.E. provided the control technology base for the navy by applying the then existing control theory with new designs to follow as technology is updated. Improvements have been implemented on the engine to increase horsepower, weight reduction and other peripheral systems but there has been no major design change to the control system up to and including the DDG-51.

This report will look at modern day aero approaches to control theory to see if they could be applied to naval marine propulsion systems. The theory and the implementation will both be reviewed.

This paper is a review of published literature on modern control analysis for non linear systems. Proprietary analyses unquestionably exist, but were not sought out for the purposes of the present review.

Theory: The marine propulsion gas turbine requires a regulator for its control action as opposed to servo control. Servo control is a slave/master relationship with the requirement of a fast response to a quickly changing input. A regulator action is typified by a timely response to a slowly changing input. A servo control might be used in a flight control system, where a regulator is suited as a Marine Propulsion Gas Turbine controller.

Since both the marine propulsion gas turbine and the aero gas turbines are in reality non-linear, Multiple Input Multiple Output (MIMO) systems, the standard linear Bode and S-plane analysis cannot be applied. Further, since there is not in existence an accepted nonlinear control design method to use, other approaches must be developed. Typically, low order linear models are formed by "linearizing around a point," this forms the basis for the point design of Linear Quadratic Regulator (LQR) theory (4). LQR theory has been successfully applied in a number of programs, specifically the F-100 turbofan engine (Fig. 1), for the F-15 and F-16 Air Force fighter planes, and theoretically applied to multivariable control of VTOL approach for shipboard landing (5). Optimal servo control has been applied to a gasoline engine test bed by members of the faculty of engineering science, Osaka University in Japan (6). A

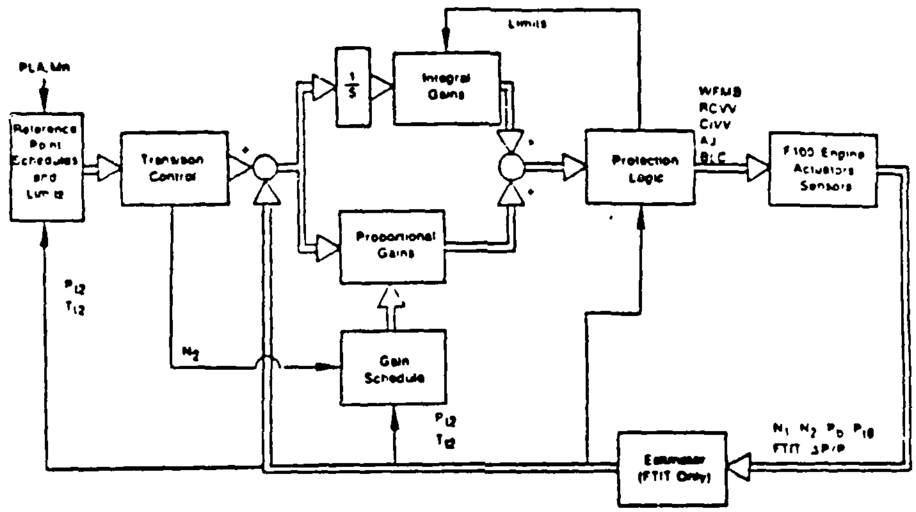


Fig. 1. F-100 Control Model

major key to the F100 design approach was the technique of gain scheduling. This technique was the link used to mate the Linear Theory of LQR with the non linear system. In the controlled system, the transition control block of Fig. 1 was used to control gain switches through the gain schedule block. Here, the gain schedule was a map of inputs versus states (Fig. 2) with gains being assigned to an area on the grid. So, for a given input the transition control selected the correct gain for stable control.

The LQR theory used to design the system of Fig. 1 optimizes the controller design based on inputs of various matrices and a performance/cost function. In fact, each of the previously mentioned applications started with a basic system model which was controllable and observable:

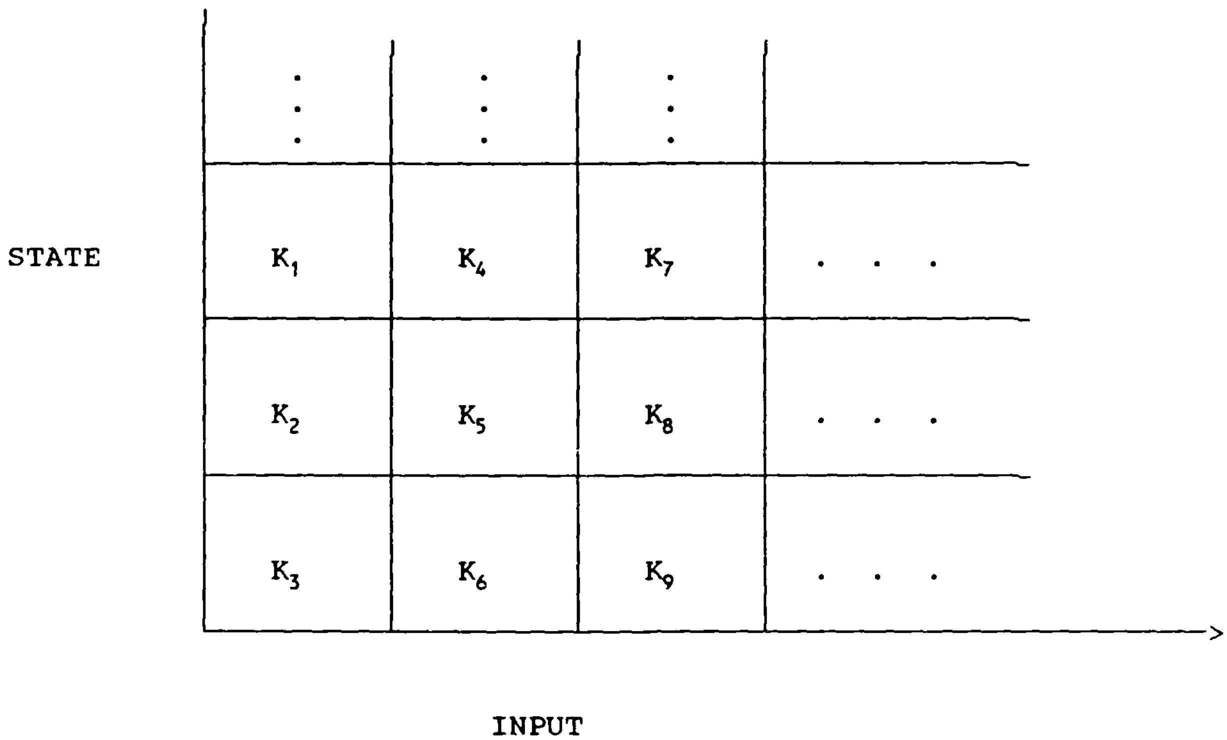


Fig. 2. Gain Schedule

$$\underline{X}\ (t) = \underline{A}\ \underline{x}\ (t) + \underline{B}\ \underline{u}\ (t) \qquad \text{Plant Model}$$

$$\underline{Y}\ (t) = \underline{C}\ \underline{x}\ (t) \qquad \text{Observed Plant Response}$$

where A, B, and C are state space matrices.

The general system description is shown in Fig. (3). A Kalman filter (estimator) must be used when the system output variables to be regulated are states which cannot be measured (4), or if the measured quantities are not states, as in the marine propulsion case (5).

The basic problem is posed as the minimization of a single-valued performance/cost index equation of the form:

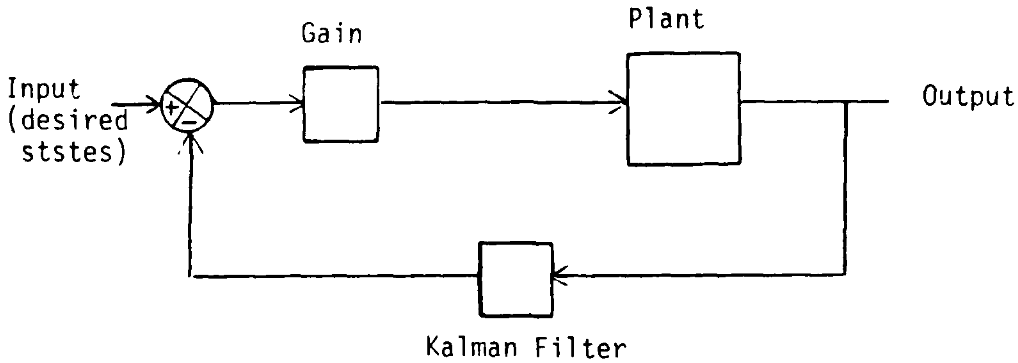


Fig. 3 - Basic Control Model

$$J = \int_0^\infty (\underline{x}^T \underline{Q}\, \underline{x} + \underline{u}^T \underline{R}\, \underline{u})\, Dt \quad \text{Both Q and R Matrices} > 0$$

The solution to this problem is:

$$\underline{u}(T) = -\underline{K}\, \underline{x}(t) = -\underline{R}^{-1} \underline{B}^{-T} \underline{P}\, \underline{x}(t)$$

where P is the solution to the riccatti equation:

$$\underline{O} = -\underline{P}\, \underline{A} - \underline{A}^{-T} \underline{P} - \underline{Q} + \underline{P}\, \underline{B}\, \underline{R}^{-1} \underline{B}^{-T} \underline{P}$$

The $\underline{R}$ matrix accounts for the expenditure of energy of control signals. These matrices, R and Q, are symmetric weighting matrices. They are assigned by the choice of the system designer and are balanced, or weighted, to produce the desired results. The minimization of the performance/cost index, determines the elements of the K matrix. These gains are the object of the controllers design. The gains are then used in simulating the response of the nonlinear controlled system. A cut and try approach is used to choose R and Q until the simulated response is close to a desired response.

Ongoing work at the Naval Postgraduate School using a Boeing 502-6a test facility, (Fig. 4), emulating marine propulsion using a water brake dynamometer for propulsion load, has produced results which lend stre‵.,th to the LQR design theory (ref. 3). Through hardware and software implementation a data base has been generated which when compared to a present computer simulation technique has shown near linearity. Fig. (5)

IMPLEMENTATION: Control systems for marine gas turbines are for the most part aero derivative systems which were developed over two decades ago. The aero community has progressed forward to the from the old analog systems to advanced digital systems through the use of microprocessors. This approach could be a new design course for the U.S. Navy's marine gas turbine program. Though the aero community started work in this direction the marine gas turbine community was divided on the direction to proceed. One side supported analog control citing it's ability to handle any necessary computations for control. Analog support triumphed and General Motors opted for this direction resulting in the LM-2500 control system used up through the DDG-51 today.

Fig. 6 depicts type of controller found on today's U.S. Navy FFG-7 class ships. (7)

Analog design technology begins with a configuration of standard building blocks based on analog hardware components and modular construction techniques. When hardware changes are required, production delays result as well as causing back-up.

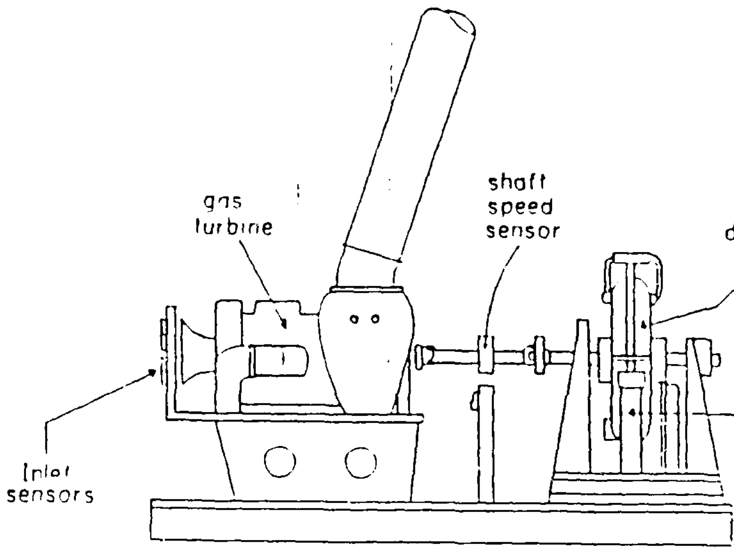


Fig. 4. Test Bed Simulation.

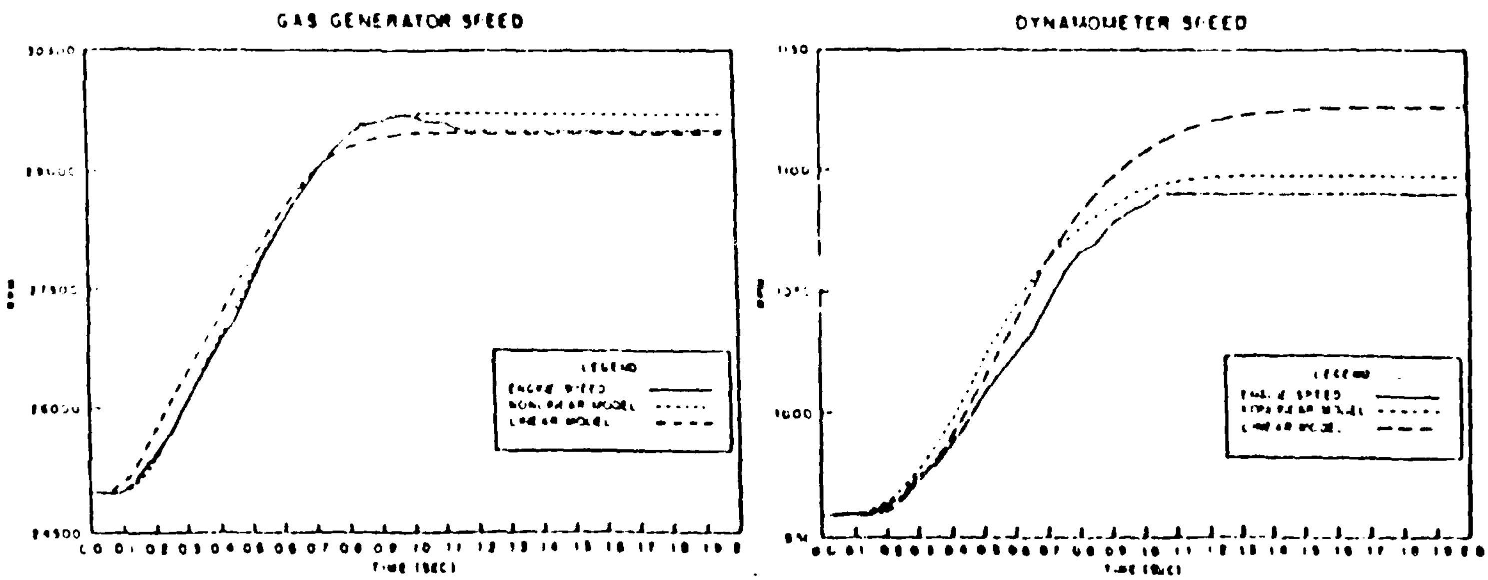


Fig. 5. NPS boeing 502-6A computer Simulation Results.

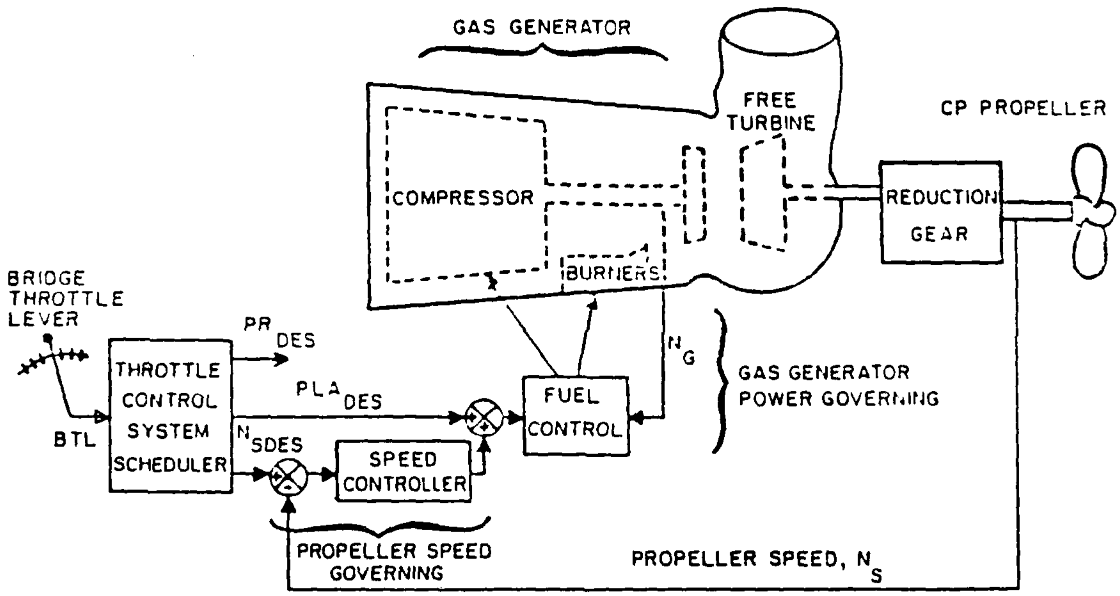


Fig 6. FFG-7 System Model

support revisions (technical manual changes), and requiring additional technical training. The end result may not be the best control system and quite possibly very expensive. Analog control systems are not very adaptable and any design changes may be major. On the opposing side are the proponents of digital theory believing that a digital based system would be faster, less expensive and more universal in its application. The aero community decided to advance in this direction. With the advent of the microprocessor, and its reliable and inexpensive computing power, the aero control designers found a control system which overrides the disadvantages of the analog system. A significant improvement in cost, reliability, and performance (shown in Fig 7 (8)) resulted. This has been demonstrated by use in a number of

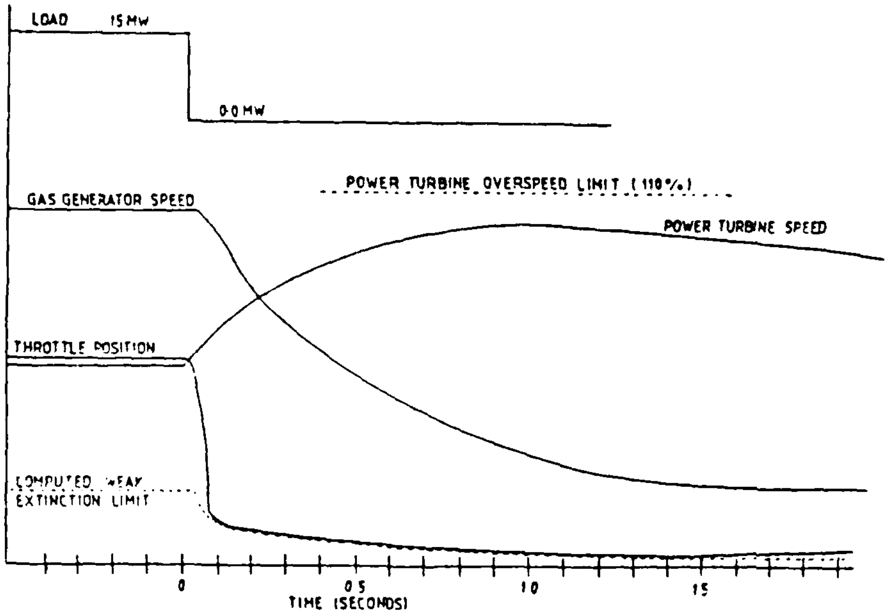


FIG. 7 Typical Load Rejection Response

applications. The first was the F-100 turbofan engine currently installed in the F-15 and F-16 aircraft (4). The second application was by Nagoya Aircraft Works of Mitsubishi Heavy Industries Ltd. of Japan. They successfully demonstrated digital control of small gas turbine engines, specifically 30 hp and 1000 hp. An Intel 8085 microprocessor was used and their achieved success clearly supports the use of digital controls to reduce the cost, increase the reliability and flexibility, as well as reduce the size and number of components (9). Finally, a third application of a digital control system was specifically designed for research on advanced digital control logic. This research involved a small turboshaft engine, the General Electric YT-700, used for small helicopters (10). A 2500 HP dynamometer was used to

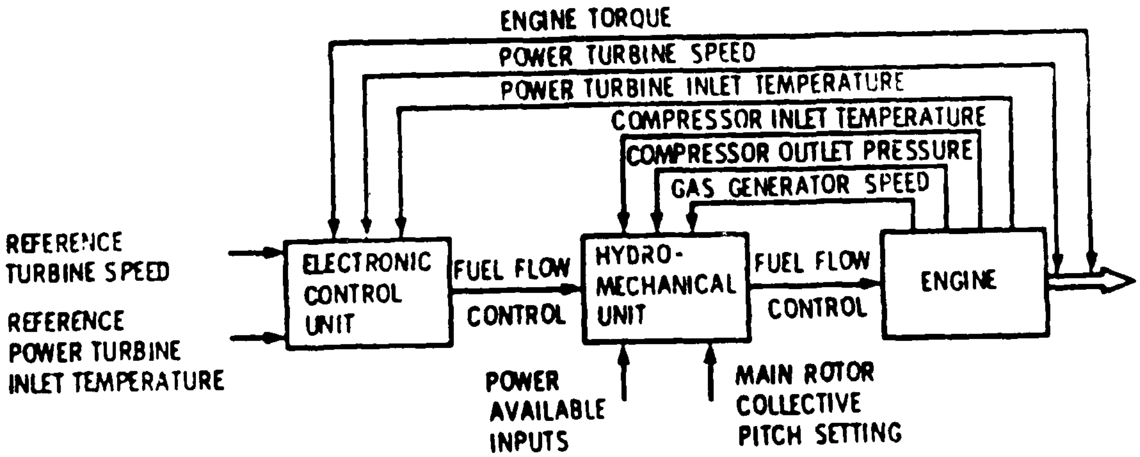


Fig. 8 YT-700 Control System Concept

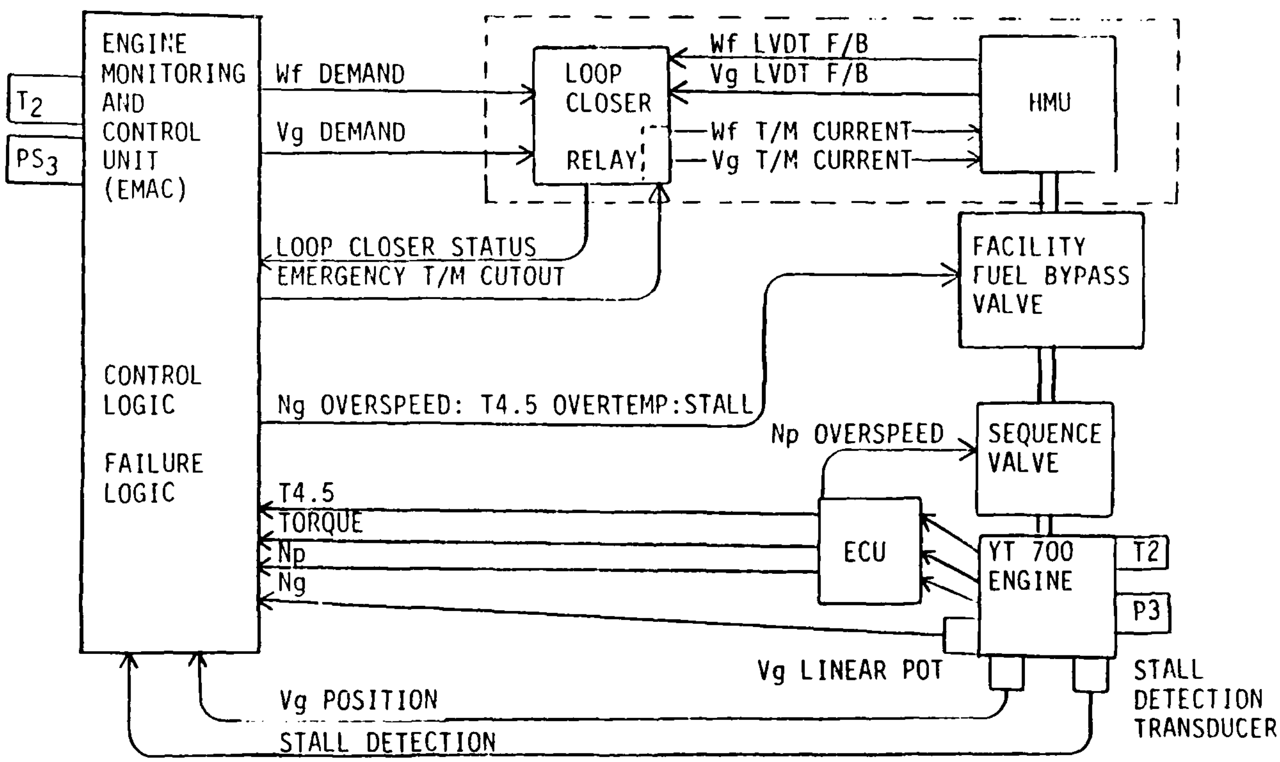
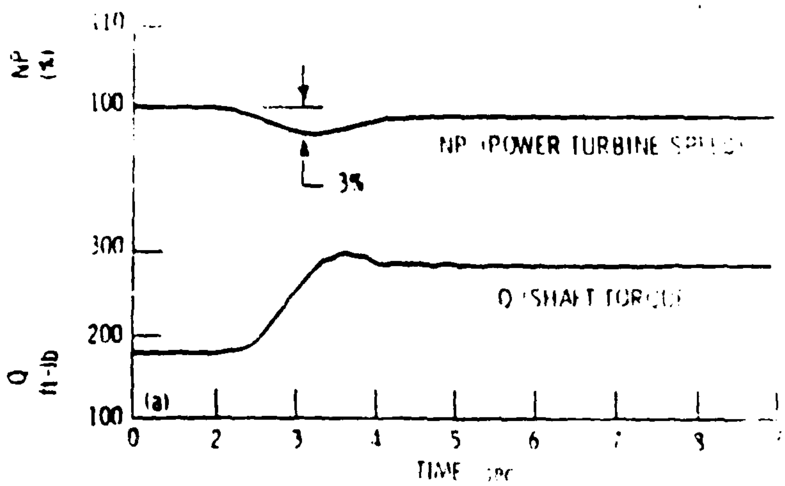


Fig. 9 YT-700 Control System Implementation

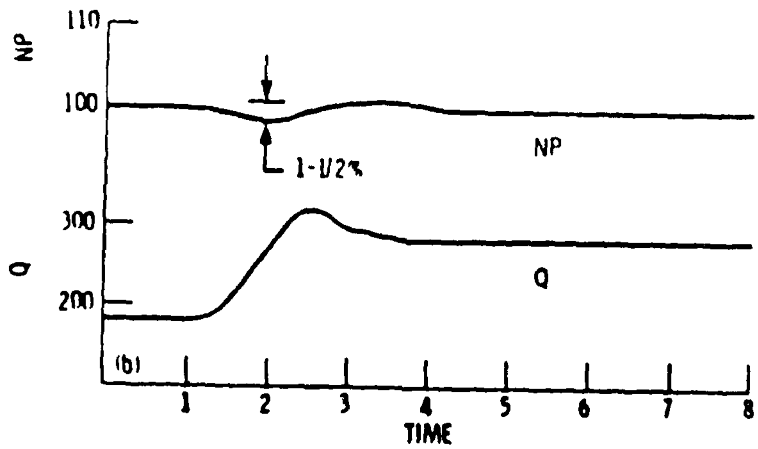
absorb engine shaft horsepower (similar to the waterbrake dynamometer use simulating propeller shaft loads at the Naval Postgraduate School (7)). Their purpose was to show improved power turbine speed governing when compared to existing baseline control data. An Intel 8085 microprocessor based control system was designed and is represented in Figures 8 and 9.

The results of the evaluation of the YT-700 digital controller (Fig. 10) show reduced power turbine speed droop caused by unexpected load changes. This realtime simulation and comparison to base-line data also supports the case for developing controllers with digital theory for marine gas turbine applications.

SUMMARY AND CONCLUSION: With the total ship system engineering concept being developed for the future of U.S. Navy ship design (11), a new control design approach for the marine gas turbine should be developed. This design approach should take advantage of the large scale integration of new computer methods for matrix and vector manipulation to provide a more large scale control for gas turbines. This approach is ideal for a turbine controller based on LQR theory. This should be accomplished simultaneously with the other ship design requirements for future naval war ships. The marriage of Linear Quadratic Regulator theory and digital control implementation, with their distinct advantages, should provide for a more efficient, reliable, less costly, and more dynamically flexible control system. If more efficient control of fuel flow is
realized the implications to present and future naval warships



(A)



(B)

(A) Typical steep turn or approach transient-baseline data
(B) Typical steep turn or approach transient - multi-input system

Fig. 10. Comparison of Rotor Speed Responses for Baseline and Multivariable Control Systems.

would be enormous. With fuel costs rising and the defense budget shrinking, two benefits could be realized. The first would be a lower fuel budget while the second might be an increase in at-sea training time necessary to maintain the readiness of the more modern and highly technical fleet in existence today.

LQR theory and digital control both make valuable contributions to this new approach in the marine propulsion world. In the theory half of the picture, LQR offers improved response to dynamic changes in plant parameters over present alternatives. Also, through more accurate modeling of multivariable non-linear systems, inefficient response characteristics could be further reduced. A dual mode controller (cruise and battle modes) might also be designed to provide for the two principle operating requirements of a naval warship by adjusting the gains to achieve these modes. Weighting in one direction would provide efficient cruising while weighting in the other direction would allow for quick response for battle conditions. For digital implementations, more modern, faster microprocessors with even greater computing power than those discussed herein exist today. Since digital control was successfully realized with the older models it stands to reason that the new ones will provide for even more efficient control. Thus, for the above reasons it is strongly recommended that further development work be invested in the implementation of LQ controllers in digital hardware for marine gas turbine propulsion systems.

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